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Comparative soil quality in maize rotations with high or low residue diversity

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Abstract This study assessed differences in soil quality linked to differences in the diversity of residues returned to the soil in nine pairs of farm fields in central Michigan. To assure that management was the main difference within pairs, study sites were selected that mapped to the same soil series. Analysis of variance using subsamples as replicates for all nine comparisons revealed significantly higher maize (*Zea mays* L.) yield and total and mineralizable N for the high-diversity fields. Manuring history reported by farmers was difficult ro reconcile with levels of total C and extractable P. To account for uncertainty in manuring histories, comparisons were separated into four subsets on the basis of residue diversity (DVS) and extractable P (high DVS high P, low DVS low P, high DVS low P, and low DVS high P). For these segregates, analysis of variance (ANOVA) using subsamples as replicates revealed significant improvements in 6 of 21 soil quality indices in the high-DVS-P subset. For all nine comparisons, correlation analysis revealed moderately strong relationships between total C, extractable P, as well as their ratio (C_{tot}/P_{ext}), and both bulk density and log(infiltration time). When the data were segregated as before, these relationships were much stronger for the high-DVS high-P subset, and their slopes differed significantly from those of the other subsets, indicating that the data points originated from different populations. These results suggest a strong interaction between residue diversity, and P likely applied in manure, that influenced soil quality.

Key words Soil properties · Minimum data set · Soil quality · Paired comparisons · Cropping diversity · Mineralizable N · *Zea mays* L. · Manuring histories

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Introduction

Management strategies to sustain or improve soil quality usually call for increasing the diversity of cropping by intercropping and using cover crops in rotations. Increasing the diversity of cropping may help increase the amount, quality and variety of residues returned to the soil, and lengthen the time that roots are active during the growing season. This can protect the soil, reduce erosion, increase organic matter and water retention, and increase the efficiency of nitrogen utilization in the soil (Karlen et al. 1992). However, the paucity of species in cropping systems greatly restricts the potential for spatial diversity, and underscores the importance of temporal diversity in rotations.

It is now recognized that the linkage between plant diversity and decomposer organisms may be a key control in managed ecosystems (Swift and Anderson 1993). Because decomposition processes are regulated to a large extent by the physical and chemical properties of residues and exudates, a wide range in properties can result in a diversity of decomposition rates. This diversity in decomposition rates has been hypothesized to directly control the availability of nutrients to plants and the stability of nutrient cycling in agricultural systems (Swift and Anderson 1993).

While it is thought that the robustness of agricultural systems can be improved by imitating the variety in natural ecosystems, little information is available about how diversity in crop rotations, and thus the mix of residues returned to the soil over several growing seasons, affects soil quality. One approach towards assessing soil quality has been to develop a minimum data set (MDS) of soil physical, chemical and biological properties using standard methods and procedures (Doran and Parkin 1994; Larson and Pierce 1994). The aim of this research was to use the MDS approach to compare adjacent farm fields, in order to test whether diversity in residues returned to the soil during a single cycle in maize rotations can be linked to improvements in soil quality.

Materials and methods

The study area was in south-central Michigan, where winters are cold and summers temperate. Daily temperature fluctuations in January range from 0 to 10 °C, and in July from 23 to 11 °C. Annual precipitation averages approximately 75 cm, with some 45 cm falling during the growing season. Soils developed on sandy or calcareous glaciopluvial deposits, and are poorly to well drained and slowly to moderately permeable.

Site selection

In selecting fieldpairs for comparison, we attempted to minimize differences in soil-forming factors and to maximize difference in residue management. The candidate fields' histories of main and cover cropping and manuring were recorded for the years 1989–1993 by interviewing farmers and extension agents. To verify that the potential paired fields were on the same soil series and had similar aspect and topographic position, we consulted soil survey maps and made observations in the field. Field pairs were selected that were mapped as the same soil series and were located a closely as possible, although distances between study sites varied from 0.1 to 2 km (Table 1). Experience gained in selecting and sampling sites for paired comparisons during a preliminary study the previous year (Willson et al. 1993) demonstrated the need to limit sampling to the maize phase of the rotation. Most of the farms selected were conventional; of two "alternative" enterprises, one was a certified organic farm.

Diversity in residues returned to the soil was estimated by summing sources of residue C. Each crop or cover crop species used in the rotation, as well as any manure applied, was considered as one additional source of residue diversity. To be selected for comparison, field pairs were required to have a minimum difference of two points in residue diversity. Cropping and manuring histories were mostly reconstructed from farm records, but in some instances were based on memory. This led to selections being made in the field on the basis of information which was later discovered to be erroneous, and resulted in two comparisons that had diversity differences of only one point (Table 1).

Table 1 Landscape and soil characteristics, and 1989–1993 history of cropping and manuring of study sites in south-central Michigan

Comparison	Landscape	Distance between sites (~m)	Soil series[ab] (% slope)	Determined texture[b] (% gravel-sand silt-clay)[c]	Main crops[d]	Cover crops[e]	Manure[f] (~Mg ha^{-1}) (wet)	Residue diversity[g]
Control	Nearly level	40	Kalamazoo sl (0–2%)	cl (1-26-44-30)	A A A A M	– – – – –	– – – – –	2
Control	Nearly level		Kalamazoo sl (0–2%)	l (15-42-33-25)	A A A A M	– – – – –	– – – – –	2
1 high	S shoulder, small knoll	200	Spinks ls (0–6%)	ls (2-86-7-7)	T S M S M	– – – – –	–25–25–	4
1 low	S shoulder, small knoll		Spinks ls (0–6%)	ls (2-87-7-6)	M M M M M	– – – – –	25 25– – –	2
2 high	Nearly level bottom	200	Capac l (0–3%)	cl (1-40-24-35)	M M S W M	cl – – cl cl	– – – – –	4
2 low	Nearly level bottom		Capac l (0–3%)	scl (1-53-18-29)	M M M M M	– – – – –	25 25 25 25 25	2
3 high	Nearly level	100	Capac l (0–3%)	scl (16-49-21-29)	M M S W M	cl – – cl cl	– – – – –	4
3 low	Nearly level		Capac l (0–3%)	scl (4-51-23-36)	M S W M M	– – – – –	– – – – –	3
4 high	Rolling, mid-slope	100	Marlette fsl (2–6%)	sl (10-67-23-10)	M S M S M	cl – – – –	– – 25 – –	4
4 low	Rolling, mid-slope		Marlette fsl (2–6%)	sl (6-66-24-11)	M M M M M	– – – – –	25 25 25 25 25	2
5 high	Nearly level	1000	Capac l (0–3%)	scl (3-45-27-28)	M S W M M	– – cl cl cl	– – – – –	4
5 low	Nearly level		Capac l (0–3%)	scl (3-53-25-22)	A A A M M	– – – – –	25 25 25 25 –	3
6 high	Small undulations	150	Ithaca l (0–3%)	scl (8-46-22-31)	C W M S M	– – – – –	– – – 25 –	5
6 low	Small undulations		Ithaca l (0–3%)	scl (1-52-21-27)	M M S M M	– – – – –	– – – – –	2
7 high	Nearly level	2000	Kalamazoo sl (0–2%)	sl (1-58-25-17)	M M W M M	– – cl – –	25 – 25 – –	4
7 low	Small undulations		Kalamazoo sl (2–6%)	sl (6-56-26-18)	M M M M M	– – – – –	– – – – –	1
8 high	Small undulations	1000	Capac l (0–3%)	cl (6-39-33-29)	M B C W M	– – – cl –	25 25 25 – –	6
8 low	Small undulations		Capac l (0–3%)	sl (6-54-28-18)	M M M M M	– – – – –	25 25 25 – –	2
9 high	S shoulder, small knoll	400	Marlette fsl (2–6%)	sl (17-64-20-16)	A W M S M	og v – – v	– 12.5 – – –	7
9 low	S shoulder, small knoll		Marlette fsl (2–6%)	sl (10-58-23-19)	W F M S M	– – cl – –	– – – – –	4

[a] *Capac* fine-loamy, mixed, mesic Aeric Ochraqualfs, *Ithaca* fine, mixed, mesic, Glossaquic Hapludalfs, *Kalamazoo* (fine-loamy, mixed mesic Typic Hapludalfs, *Marlette* fine-loamy, mixed, mesic Haplic Glossudafs, *Spinks* sandy, mixed, mesic Psammentic Hapludalfs

[b] *c* clay, *f* fine, *l* loam(y), *s* sand(y)

[c] Bulked samples (sand+silt+clay = 100%)

[d] *M* maize, *S* soybeans, *A* alfalfa, *W* wheat, *T* triticale, *B* dry beans, *C* cucumbers, *F* fallow

[e] *cl* clover, *og* orchard grass, *v* vetch

[f] Manure was from on-farm dairy or hog operations, and it was assumed that the type applied did not change from year to year

[g] Sum of different sources of residue C from main and cover crops and manure (crop and cover crop species = 1, manure = 1, fallow = 0)

Methods

Six sampling stations were installed in study of plots of ~0.1 ha in each field. Sampling stations were installed in the interrow spaces in three pairs, each pair separated by 12 rows (~10 m); the interrow distance between stations was 6.8 m. Sampling stations consisted of the area within 50 cm of the single-ring aluminium respirometer-infiltrometer (15 cm diameter × 15 cm height) installed ~7.5 cm deep in the center of the interrow space. Sampling stations were located in the center of the interrow because differences in the geometry of ridges, on which maize was generally planted, made matching the placement of the infiltrometer-respirometer difficult otherwise. Another reason for selecting the interrow space was our interest in testing for the legacy of residues returned during the past five growing seasons; this effect would likely be less noticeable within the maize row. Interrows were selected only after considerable trial and error, and were generally non-wheel track rows, free from obvious disturbances such as fertilizer bands, etc.

We sampled from late June to early August 1993, when maize was actively growing and was generally >1 m tall. Personnel were trained by conducting a trial in a satellite maize field of the Living Field Laboratory (LFL, Kellogg Biological Station, Hickory Corners, Michigan) managed identically to one of the experimental treatments at the LFL. Measurements were taken in two locations in that field, which although separated by distance of ~40 m and on supposedly "uniform" soil, differed visibly in maize growth. Those measurements, which highlight spatial variability in soils, were used as controls for the nine comparisons (Table 2).

The minimum data set and methods used were essentially as proposed by Doran and Parkin (1994), with procedures (which were then under development) generally as in Doran (1995). In addition, we measured surface penetration resistance, and installed two additional double-ring infiltrometers (data not shown). Soil samples (0–20 cm), as well as other measurements, were taken from the interrow area 30–50 cm from the respirometer/infiltrometer (i.e., sampling station). Bulked soil samples (~500 g) were kept over ice in the field until transported to the laboratory, where portions to be used for measuring biological properties were stored ad ~4 °C. Laboratory methods of soil analysis were generally as in Page et al. (1982). Soil properties were analyzed as follows: bulk density by pushing a small, bottomless aerosol can approximately 7.5 cm into the soil, and removing the soil quantitatively after measuring the length of head space; texture by the hydrometer method; water-holding capacity by using pressure plates to determine water content in undisturbed soil cores at 30 kPa and in packed samples bulked from the six soil samples at each plot at 1.5 MPa; penetration resistance by using a Soiltest CL-700A pocket penetrometer ($n=6$ at each station); depth of topsoil and of maize rooting by digging two small pits at each station; infiltration rate by measuring the time required for 2.5 cm of water added at once to enter the soil in the (single-ring) infiltrometer; inorganic N ($NO_3^-+NO_2^-+NH_4^+$) by extracting with 2 *M* KCl and using automated colorimetry; mineralizable N by anaerobic incubation at 37 °C for 7 days (Keeney and Nelson 1982); total C by high-temperature combustion (Dohrmann DC 190); total N by the Kjeldahl procedure; extractable P by the Bray procedure; soil respiration by taking samples in the infiltrometer headspace after 1 h incubation and measuring CO_2 by gas chromatography; microbial biomass by measuring CO_2 evolved by 20-g subsamples of moist soil during 10 days following fumigation with chloroform (Parkinson and Paul 1982); and CO_2 evolved by unfumigated subsamples during the same period was used as a measure of respiration rate of the soil microbial biomass. The soil infiltration and respiration rate measurements were made in the early morning and repeated in the early afternoon 4–6 h after the first irrigation. Infiltration data were transformed to the $\log_{10}$ form, and microbial biomass C to the square-root form in order to obtain normal distributions for analysis. Statistical significance reported refers to the transformed data. Infiltration rates were calculated back from the transformed data. Maize grain yield was measured by hand-harvesting 6.8 m of row ($n=4$) in each study site.

For the purposes of this study, higher soil quality was indicated if the topsoil was deeper, had a lower surface bulk density or resistance to penetration, or higher water-holding capacity or faster infiltration, had a higher concentration of organic C or nutrient availability (higher N_{tot}, N_{ext}, P_{ext}, N_{min}, lower C:N ratio, higher N_{min}/C_{tot}), had a higher microbial biomass C, or higher microbial respiration rate (but lower specific respiratory activity), or had a higher ratio of microbial C to total C (C_{mic}/C_{tot}), higher soil respiration rate, or higher maize yield.

Results and discussion

Soils were generally of medium texture and density, non-saline (EC≤0.1 dSm^{-1}, data not shown), slightly acid to neutral, and fertile (Table 2). Although the study sites were selected so that they mapped to the same soil series, textures differed in two of the nine comparisons. Gravel content, which affects soil-water relations, also differed in several comparisons.

Within-pair comparisons, high vs low diversity

The six sampling-station measurements were used to compare within-pair means by the paired comparison *t*-test (Table 2). Differences in variances were also checked by the *F*-test (not shown). Some significant differences in means and variances were found for nearly all indices. However, only the means of extractable N and extractable P, and the variances of pH and extractable N, differed in the majority of comparisons. Except for comparisons 3 and 7, which showed improvement in 9 of the 22 indices analyzed, few patterns could be discerned in the within-pair comparisons. Nonetheless, the majority of significant differences in means lay in the direction of improved soil quality for the fields receiving a high diversity of residues. Except for lower pH, the means of the controls were similar to the average soil properties for the nine comparisons (Table 3). Of the 22 indices determined, the number of significant differences in the controls was 3, while the average for the 9 comparisons was 5.5.

At some sites, high and variable concentrations of extractable N and P were encountered. In the case of N, this may have been due to unintentionally sampling near fertilizer bands. But the high concentrations of extractable P were likely due to long-term manuring, which in some cases may have occurred more than five growing seasons before our study. Spatial variability in manure application may help explain the high variability in concentrations of extractable P found at some sites. The low concentrations of mineralizable N encountered may have been due to sampling during midsummer, when active maize growth might have depleted that pool.

Comparisons across fields, high vs low diversity

Analysis of variance

When means were compared across fields by analysis of variance (ANOVA) in a 9 × 2 block design ($n=18$), no significant differences were found between high- and low-

Table 2 Paired comparisons of soil physical, chemical and biological properties in maize fields with high or low diversity of residues returned to the soil during 1989–1993. Values are means ($n=6$) for the 0- to 20-cm soil layer unless noted otherwise

Comparison	Residue diversity	pH	Bulk density (0–7.5 cm) (g cm^{-3})	Penetration resistance (kg cm^{-2})	Water-holding capacity (cm)	Topsoil depth (cm)	Maize rooting depth (cm)	Infiltration rate (cm min^{-1})		Maize yield[c] (Mg ha^{-1})	Total C (Mg ha^{-1})	Total N (Mg ha^{-1})	Extractable N (kg ha^{-1})	Mineralizable N (kg ha^{-1})	Extractable P (kg ha^{-1})	Microbial biomass C (kg ha^{-1})	Soil respiration (kg CO_2-C ha^{-1} day^{-1})		Microbial respiration	Specific respiratory activity[e]	Mineralizable N/total C (mg N g^{-1} C)	C:N (w/w)	C_{mic}/C_{total} (%)
								Initial[a]	After irrig.[b]								Initial	After irrig.					
Control	Low	5.2	1.05	0.9	1.90#	nd	24.8	3.7**	0.4	nd[d]	29.1	2.84**	46.9	28.9	108	935	40.9	24.7	16.9	18.0	0.99	10.3	3.22
Control	Low	5.4	1.25**	1.0	1.25	nd	25.8	0.2	0.9	nd[d]	26.1	2.46	44.5	29.2	119	947	33.4	18.6	22.9	24.6	1.12	10.6	3.72
1	High	6.5#	1.38	Wet nd	0.98	25.9	23.3	0.4	0.4	5.56	19.3	1.33	29.1	14.4#	506#	720	17.2	10.8	23.9	36.1	0.75#	14.7	3.77
1	Low	5.8	1.43#	Wet nd	1.02	28.5#	23.3	0.4	0.3	7.35#	21.7	1.73*	191	3.3	436	811	17.3	8.83	33.1**	50.2	0.15	12.6	3.81
2	High	6.9	1.01	0.89	2.29	26.3	21.8	23.2	9.4	10.8*	48.4	6.01	50.0*	36.6	157	1338	23.8	10.6	21.7*	16.9#	0.74#	8.4	2.77
2	Low	7.1*	1.03	0.46	1.69	31.4*	22.0	11.4	7.2	8.9	45.5	4.62	36.9	30.1	118	1153	30.4	15.8#	8.90	7.77	0.67	9.9*	2.58
3	High	6.3	1.06	0.67	1.20	30.0	24.8	17.5*	3.4*	11.1**	34.2	3.66	243#	27.0	92.2*	1054	42.4	18.0	11.4	10.5	0.79	9.4	3.17**
3	Low	6.5	1.29*	2.40*	1.34	29.8	22.6	0.6	0.1	5.84	35.3	3.43	14.3	27.4	77.1	974	29.7	13.9	10.3	10.6	0.78	10.3*	2.79
4	High	5.9	1.26	1.86	2.48	25.1	19.7	1.7	0.9	10.7	34.4#	2.86	24.6	40.0	252	749	32.8	10.5	5.87	7.37	1.23	11.9	2.37
4	Low	5.7	1.25	1.06	2.20	22.8	22.8#	3.7	1.7	10.1	27.9	2.58	29.6	48.6	990**	877	27.9	6.68	9.75	10.9#	1.71	10.8	3.15
5	High	6.4	1.15	1.88	1.52	28.6	23.2	7.8	3.0	11.1*	31.7	2.96	39.4	19.0	120	1081	22.2	3.08	13.4	11.8	0.60	10.8	3.42
5	Low	6.3	1.29	1.84	1.51	28.1	25.4**	12.2	7.4	6.48	36.2	3.67*	207	30.7	119	1133	34.8	32.4**	13.2	12.0	0.84	9.9	3.16
6	High	6.1	1.25	0.36	1.10	25.3	25.1	1.0	0.3	10.3	32.7	3.61	63.5	24.0	176*	664	39.9	6.21	9.50	18.0	0.75	9.1	2.02
6	Low	5.8	1.23	0.83**	1.49*	23.8	23.8	1.3	0.3	9.74	34.4	3.20	52.0	18.8	126	617	60.3#	6.86	9.17	15.5	0.56	10.7**	1.85
7	High	5.6	1.44	0.93	1.99*	29.8*	27.8**	0.3	0.1	8.23	35.3**	3.36**	29.9	49.9*	567*	909**	27.7	29.6*	22.7	24.8	1.44	10.5	2.58
7	Low	6.1	1.40	1.48	1.38	26.7	21.8	0.3	0.1	7.15	21.2	2.11	22.8	30.1	135	567	31.1	15.0	10.2	19.1	1.43	10.0	2.69
8	High	5.8	1.29**	1.08*	1.72	26.1	22.6	0.9	0.1	10.3	38.2	3.49	81.4#	26.2	170	848	37.1	15.4	13.8	16.0	0.68	10.9	2.23
8	Low	6.8	1.15	0.59	2.36#	24.4	20.9	3.3	0.2	10.7	34.4	3.23	31.5	25.8	355**	1000#	27.1	11.4	16.4	16.8	0.75	10.7	2.93#
9	High	5.8	1.27	1.03	2.18*	21.6	20.1	1.8	0.3	5.48	21.2	2.09	28.7	29.0**	58.8	737#	64.2	12.5	7.96	10.7	1.39**	10.1	3.51
9	Low	5.9	1.20	0.72	1.00		23.9**	23.3**	1.2	0.4	8.22*	21.2	2.10	94.9*	18.3	171**	579	45,7	11.0	5.36	9.67	0.87	10.1
2.80																							

[a] Falling head, 2.5 cm H_2O
[b] 4–6 h after initial irrigation
[c] $n=4$
[d] Yield averaged 8.53 Mg ha^{-1} at adjacent experimental field trials under the same management
[e] mg CO_2-C g^{-1} C_{mic} day^{-1}
#, *, ** significant at the 0.1, 0.05 and 0.01 levels, respectively (symbols arbitrarily placed on larger value); *nd* not determined

Table 3 Comparison of soil properties in maize-based rotations with high or low diversity of residues returned to the soil, analyzed by two-way ANOVA procedures using subsamples as replicates

Soil property	All nine comparisons			High DVS P>low DVS P (comparisons 1,2,3,6,7)			Low DVS P≥high DVS P (comparisons 4,5,8,9)		
	High diversity	Low diversity	Ratio H/L	High diversity	Low diversity	Ratio H/L	High diversity	Low diversity	Ratio H/L
Bulk density (g cm^{-3})	1.24	1.25	0.99	1.23	1.28#	0.96	1.24	1.22	1.02
Penetration resistance (kg cm^{-2})	0.97	1.04	0.93	0.57	1.03**	0.55	1.47	1.05	1.40
Maize rooting depth (cm)	23.1	22.9	1.01	24.6*	22.7	1.08	21.4	23.1**	0.93
Topsoil depth (cm)	26.5	26.6	1.00	27.5	28.0	0.98	25.3	24.8	1.02
Water-holding capacity (cm)	1.72	1.54	1.12	1.51	1.39	1.09	1.98	1.72	1.15
Infiltration rate (cm min^{-1})	2.21	1.77	1.25	2.21#	0.99	2.23	2.20	3.66	0.60
Infiltration rate after irrigation (cm min^{-1})	0.68	0.58	1.17	0.81#	0.38	2.16	0.55	1.00	0.55
pH	6.0	6.0	1.00	6.1	6.0	1.02	5.9	6.0	0.98
Total C (Mg ha^{-1})	32.8#	30.9	1.06	34.0	31.6	1.08	31.4	29.9	1.05
Total N (Mg ha^{-1})	3.27*	2.96	1.10	3.60**	3.02	1.19	2.85	2.90	0.98
C:N ratio	10.6	10.6	1.00	10.4	10.7	0.97	10.9#	10.4	1.05
Extractable N (kg ha^{-1})	65.5	75.5	0.87	83.0	63.4	1.31	43.5	90.7	0.48
Mineralizable N (kg ha^{-1})	29.6*	25.1	1.18	30.5***	22.1	1.38	28.6	28.8	0.99
Extractable P (kg ha^{-1})	233	281	0.83	299***	178	1.68	150	409**	0.37
Soil respiration (kg CO_2-C ha^{-1} day^{-1})	34.8	33.5	1.04	30.2	33.5	0.90	41.6	33.9	1.23
Soil respiration after irrigation	13.2	13.6	0.97	15.1	12.0	1.26	10.6	15.7	0.68
Microbial biomass C (kg ha^{-1})	900	855	1.05	937#	824	1.14	854	896	0.95
Microbial respiration (kg CO_2-C ha^{-1} day^{-1})	14.5	12.9	1.12	17.8	14.3	1.24	10.3	11.1	0.93
Specific microbial respiration (mg g^{-1} day^{-1})	16.9	16.9	1.00	21.2	20.6	1.03	11.5	12.2	0.94
$C_{microbial}/C_{total}$ (%)	2.87	2.86	1.00	2.86	2.74	1.04	2.88	3.00	0.96
$N_{mineralizable}/C_{total}$ (mg^{-1} g^{-1})	0.93	0.87	1.07	0.90**	0.74	1.22	0.98	1.03	0.95
$C_{total}/P_{extractable}$ (mg mg^{-1})	228	218	1.05	199	275***	0.72	265***	146	1.82
Maize yield (Mg ha^{-1})	9.29*	8.28	1.12	9.21*	7.79	1.18	9.40	8.89	1.06

#, *, **, *** significantly different at the 0.1, 0.05, 0.01 and 0.001 levels, respectively (symbols arbitrarily placed on larger value)

diversity farming systems (not shown). The data were then analyzed in a similar 9 × 2 ANOVA, but using subsamples as replicates ($n=108$). The latter ANOVA procedure revealed higher maize yield and total and mineralizable N in the high-diversity fields ($P\leq0.05$), as well as a trend towards higher C content ($P\leq0.10$) (Table 3). In contrast, the low-diversity fields showed no improvement in any of the indices measured. The results suggest that the increase in maize yield resulted from a larger pool of organic N, because there was a significant increase in total, but not extractable, inorganic N.

The use of subsamples as replicates in paired comparisons of soil quality has been criticized (Wardle 1994). Replication is impossible when comparing fields management by different farmers. And it is unlikely that a much larger population of sites could have been sampled, given the requirement that sampling occur at all sites during the same part of the growing season. Nevertheless, tentative conclusions can be arrived at by making simple comparisons and noting trends or frequencies (Reganold 1994; Hurlburt 1984). To avoid giving the impression of statistical rigor, neither standard errors nor least significant differences are given in Table 3.

It was difficult to reconcile manuring history reported by farmers with levels of C or extractable P. For example, in at least three comparisons, one field was reported to have received manure much more frequently than its neighbor (Table 1, comparisons 2, 4 and 5). But only in comparison 4 were there significant differences in C or P; but with higher C in the high-diversity side, and higher extractable P in the low-diversity side. To account for possible differences in past manuring, the comparisons were separated into two sets; those in which the ratio of extractable P in the high-diversity field to the low-diversity field was >1 [(high DVS P>low DVS P), comparisons 1, 2, 3, 6 and 7] and those in which ratio was ≤1 [(low DVS P≥high DVS P), comparisons 4, 5, 8 and 9]. This in effect segregated the fields into four subsets: (high DVS high P), (low DVS low P), (high DVS low P), and (low DVS high P).

Analysis of variance using subsamples as replicates (5 X 2, $n=60$) revealed significantly higher scores for the high-DVS high-P subset in 6 of 21 soil quality indices measured (Table 3; since the fields were segregated on the basis of extractable P, this index could not be counted). These included higher maize yield, higher total and mineralizable N, and a higher ratio of mineralizable N to total C ($P\leq0.05$). There were also trends toward lower bulk density, faster infiltration and higher microbial biomass ($P\leq0.10$). In contrast, the only significant difference found for the low-DVS P>high-DVS P set (4 × 2, $n=48$) was deeper maize rooting for the low-diversity fields, and a trend toward higher C:N ratio for the high-diversity fields.

An additional index, the weight ratio of total C to extractable P (C_{tot}/P_{ext}), which is discussed below, also differed significantly between high- and low-diversity fields,

but in a pattern opposite to that of extractable P. Better physical, chemical and biological properties occurred mostly in the high-DVS P high-P subset; this suggests a linkage between manuring (i.e., high levels of extractable P) and residue diversity which strongly influenced soil quality. Moderately high concentrations of extractable P in the soil, when associated with high residue diversity, seemed to drive the significant improvement in total and mineralizable N mentioned earlier when all nine pairs of comparisons were considered.

Correlation analysis

Moderate to strong correlations (r=0.49–0.68, $P \leq 0.001$) were found, across all nine comparisons, between the total concentration of C in soil (and thus N) and bulk density, log(infiltration time), mineralizable N and microbial C (not shown). Similar correlations were also found between extractable P and some of those variables. But while increased C content was associated with lower bulk density and faster infiltration, higher extractable P was linked to higher bulk density and slower infiltration. A composite index, total C:extractable P (C_{tot}/P_{ext}), incorporated aspects of both indices. Like C content, a higher (C_{tot}/P_{ext}) was associated with lower bulk density (r=–0.59, $P \leq 0.001$), faster infiltration (r=–0.57, $P \leq 0.001$), higher microbial biomass (r=+0.41, $P \leq 0.01$) and specific microbial respiration (r=+0.42, $P \leq 0.01$) (n=54).

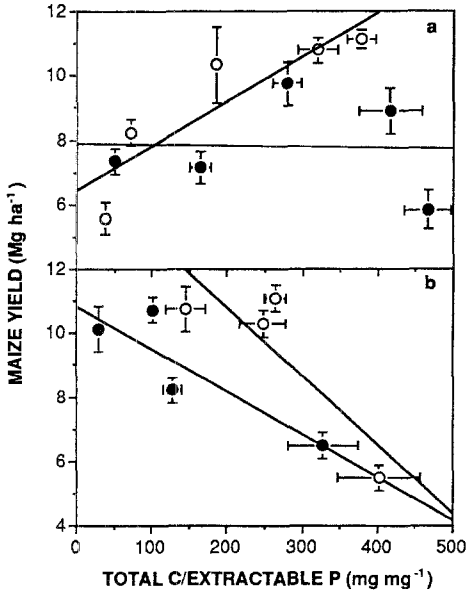

Fig. 1 a, b Relationships between mean ratio of total C to extractable P (C_{tot}/P_{ext}) in the soil and mean yield of maize. *Bars* represent±1 standard error of the mean. *Open symbols* high diversity; *closed symbols* low diversity. All high diversity (n=9): yield=8.34+0.0042 (C_{tot}/P_{ext}), r=0.23 NS (not shown). All low diversity (n=9): yield=9.33–0.0048 (C_{tot}/P_{ext}), r=0.22 NS (not shown). **a** High DVS high P (n=5): yield=6.46+0.0005 (C_{tot}/P_{ext}), r=0.89 (P=0.046). Low DVS low P (n=5): yield=7.88–0.0032 (C_{tot}/P_{ext}), r=0.04 NS. High DVS low P (n=4): yield=15.0–0.021 ($C_{tot}P_{ext}$), r=0.85 NS. Low DVS high P (n=4): yield=10.8–0.013 (C_{tot}/P_{ext}), r=0.88 NS

When the comparisons were segregated as before, the high-DVS high-P subset (n=30) had much stronger relationships for bulk density (r=–0.87, $P \leq 0.001$) and log(infiltration time) (r=–0.83, $P \leq 0.001$) than the other three subsets (r=+0.03 to –0.53, NS to $P \leq 0.001$, n=24 or 30). But, more importantly, the slopes of the relationships for the high-DVS high-P subset differed significantly ($P \leq 0.05$) from the slopes for the other subsets. This suggests that the data points originated from different populations, and thus that there exists a qualitative difference between the high-DVS high-P subset and the other three subsets. This is also illustrated by Fig. 1, which shows that mean C_{tot}/P_{ext} was positively correlated with mean maize yield, but only for the high-DVS high-P subset. No significant relationships in maize yield were found for either high or low diversity fields across the nine farms. But when the comparisons were segregated, only the slope of the relationship for the high-DVS high-P subset was positive and significantly different from zero.

Results presented here suggest that increased diversity of residues returned to the soil during a single rotation cycle improved soil quality by increasing total and mineralizable N. Better soil quality was also associated with higher maize yield. However, most of the improvement occurred in five fields – the high-DVS high-P subset – in which soils tended towards higher contents of total C and extractable P, but only moderately high C_{tot}/P_{ext}. These five fields also tended to have lower bulk densities, higher infiltration rates and higher microbial biomass than the others. Although the fields were selected to avoid, as much as possible, comparisons between "good" and "bad" farmers, it is probable that good soil quality in the high-DVS high-P subset resulted from better soil management. At the same time, some apparently well-managed fields had low soil quality. Initial soil conditions were doubtless important; but managing the quantity, variety and timing of residues returned to the soil seems to have been integral to good management.

Our results are generally consistent with those of Reganold et al. (1993), who compared conventional and biodynamic farms in New Zealand. The biodynamic farms, which used manure and cover crops to a greater extent than the conventional farms, had significantly lower soil bulk density and thicker topsoil, as well as higher soil C and N, soil respiration, mineralizable N and ratio of mineralizable N to C.

That better physical, chemical and biological properties occurred mostly in the high-DVS P high-P subset suggests a strong interaction between residue diversity and manuring which influenced soil quality. Factors such as quantity and quality of residues could not be controlled, and their effects cannot be discounted, but the cropping histories do not suggest that these factors strongly biased the results. Increasing cropping diversity by replacing maize with wheat or soybeans, while increasing the number of intercrops, would likely result in lower quantity, but somewhat higher quality, of residues returned to the soil. Moreover, the manuring histories indicate that where large differences in manuring occurred, it was the low diversity fields that generally had the higher or more frequent applications.

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